

New physics searches for the LHC

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Abstract

Data taking at the LHC is the beginning of a new era in particle physics which will lead us towards understanding the completion of the Standard Model at and beyond the TeV scale. I discuss different approaches to new physics searches: driven by experimental anomalies, driven by model building, or driven by new analysis ideas. All of them have their place as long as we keep an open mind and see their opportunities as well as their limitations.

With the LHC producing its first data relevant for physics beyond the Standard Model we are looking at exciting times for a theorist interested in understanding the TeV scale. Let me first review why the TeV scale is so interesting for particle physicists [1]: there exists a whole list of experimental and theoretical shortcomings of our Standard Model which need to be taken care of by the ultraviolet completion of our Standard Model which we should really consider an effective theory.

Experimentally, we do not understand the origin of dark matter; neither do we understand the source of flavor structures in the quark or lepton sector, the origin of the matter-antimatter asymmetry in our universe, the apparent but not quite exact gauge coupling unification, or any kind of link between our gauge theories with gravity (if that should exist). Such a list constitutes a good definition of an effective theory: a theory which has a cutoff separating the (electroweak) physics we understand and additional observations which cannot be explained.

Theoretically, considering the Standard Model an effective theory bears complications for the Higgs sector. Namely, if there exists a physical cutoff scale to the Standard Model we should be able to compute quantum corrections to the Higgs mass in the presence of this cutoff scale. Such quantum corrections have to be in part absorbed in a counter term, but given that we construct gauge theories basically to protect ourselves by *ad-hoc* appearances of unexplained cancellations we should try to protect the Higgs mass by some kind of symmetry beyond the Standard Model. This is the motivation of the many models completing the Standard Model in the ultraviolet. The corresponding mass range is the scale of new physics which comes in to protect the

Higgs mass. If we want to limit the cancellations between Standard Model and (the divergence cancelling) new physics contributions to the Higgs mass the TeV scale turns out to be the key.

This introduction fixes the structure of this talk: aside from general considerations about models visible with very little luminosity at the LHC we can follow a theoretically or an experimentally motivated path. The top forward-backward asymmetry is one example for an unexplained observation which might or might not require a new physics explanation. Dark matter is another anomaly, which we are sure exists, but which might or might not be related to the TeV scale. From a theory perspective there exist recently considered directions we can pursue, be it non-minimal supersymmetric models or additional chiral generations. Finally, from an analysis perspective there are new ideas appearing which justify a fresh look at the LHC (where the second example was only partly understood at the time of the talk but is fully discussed in these proceedings).

The ironic aspect of all of these paths is that we are missing the obvious one: if the main problem with the Standard Model occurs in the Higgs sector, why don't we find the Higgs boson first, take our time to confirm that it is a single fundamental particle [2], and deal with the theoretical complications later. This option does not exist because the Higgs boson only reluctantly couples to protons, so at the LHC we are likely to only find it after studying the TeV scale for quite a while.

1 First data: supermodels

In particular analyzing very low luminosities like 10 pb^{-1} at the LHC puts us into an awkward position. Of course we are probing a new energy scale, and of course we need to analyze data to understand the way the Standard Model look in brand new detectors, but there is simply not a lot to discover once we take into account limits from LEP or from the Tevatron. The fundamental reason is that a 7 TeV hadron collider does not simply probe all kinds of new physics which exists up to masses of 3.5 TeV in the case of pair production of new particles. Instead, most quark and gluon initiated processes happen at much lower center-of-mass energy and the few events probing larger energy scales we have to extract statistically. This means that at a hadron collider luminosity is at least as important as the proton energies, most notably for gluons where in the interesting energy range the gluon parton densities scale with the gluon-to-proton momentum fraction x proportional to $1/x^2$.

In Ref [3], which will if nothing else be remembered for its title, the authors ask the question: what kind of new physics (supermodels) can we see with at least 10 events in 10 pb^{-1} without it being ruled out by LEP, flavor physics, or the Tevatron. Of course, by now we know the answer: nothing was found. The original argument is nevertheless instructive.

To begin with, new physics particles can only be produced and decay in a few relevant topologies. If we are very limited in luminosity and energy only direct or resonant s -channel production is promising. Supermodels fulfilling the above requirements do not include pair production even of strongly interacting particles simple because the LHC cross sections are too small. Including any kind of branching ratio makes matters worse. This means that for example searches for lepto-quark pair production are not promising for very early LHC running. For example in gluon fusion resonant production of X probes the dimension-5 operator

$$\frac{g_s^2}{16\pi^2\Lambda} X G_{\mu\nu} G^{\mu\nu}, \quad (1)$$

which we know from Higgs production. This structure we can write using the effective coupling $g_{\text{eff}} = 1/(4\pi) m_X/\Lambda$. In term of g_{eff} we can estimate the reach of different partonic initial states at the LHC. For a 7 TeV the only promising initial state to produce new particles predicted by supermodels is the quark-quark

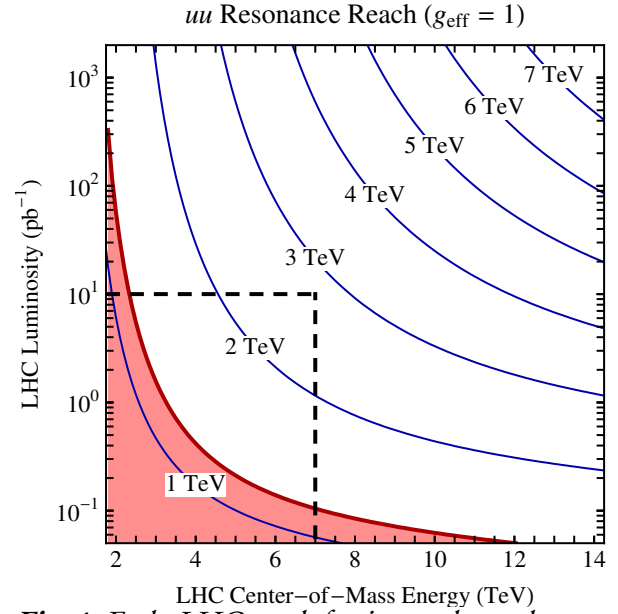


Fig. 1: Early LHC reach for in quark-quark scattering. The blue lines indicate the mass of the new particle resonantly produces. The red shaded region is ruled out by the Tevatron with 10 fb^{-1} . The dashed lines show the LHC parameters.

initial state. In Figure 1 we show how early LHC analyses can surpass Tevatron analyses in this channel. All other channels, including the usually most powerful quark-gluon initial state, are not competitive and have to wait for higher LHC luminosities.

The question remains: what are such supermodels? In resonance production we usually think of Z' searches first. However, LEP limits on the mass combined with a leptonic branching ratio solidly rule out any early LHC discovery before we even start the analysis. Instead, we can look for di-quark resonances decaying in easy to observe ways. One of them would be a di-quark D decaying via a lepto-diquark L as $D \rightarrow \ell^- L \rightarrow \ell^- \ell^+ + 2 \text{ jets}$. As strange as this signature looks it is similar to sbottom decays in R parity violating supersymmetry:

$$\begin{aligned} \tilde{b}^c &\rightarrow b \tilde{\chi}_1^0 \\ &\quad \downarrow \ell^+ \tilde{\ell} \\ &\quad \downarrow \ell^- 3j \end{aligned} \quad (2)$$

This specifically chosen fully reconstructable leptonic decay chain also leads us to a bottom line: new physics at the LHC does not only need to couple to quarks or gluons to be produced, we also need to see it in its decay products. This is where backgrounds hurt and where promising analyses die.

2 Anomaly: top asymmetry

The situation with the observed top forward-backward anomaly at the Tevatron resembles the situation with the Higgs sector and new physics at the TeV scale for the LHC. On the one hand, there exists an anomaly as an experimental puzzle, as presented at this workshop. For a forward-backward charge asymmetry which in the Standard Model is only induced at next-to-leading order [4] the observed value

$$A_{\text{FB}}^{\text{exp}} = 0.193 > A_{\text{FB}}^{\text{SM}} = 0.05 \quad (3)$$

is considerably larger than the expected value. The problem with an experimental confirmation at the LHC is that there gluon fusion usually dominates over quark-antiquark scattering which makes it hard to confirm this Tevatron measurement.

So while we would like to learn more about the asymmetry itself we will be looking for possible new physics scenarios responsible for the top charge asymmetry. This new physics has fairly specific features which are not automatically present in our usual new physics scenarios at the LHC. First, the asymmetry is large, so the responsible new physics needs to couple to quarks or/and gluons strongly enough. Second, it needs to generate a charge asymmetry with the correct sign.

The latter turns into a disappointment because there exists a prime candidate for such an asymmetry, namely an axigluon arising from a breaking of a $SU(3)_1 \times SU(3)_2$ symmetry into massless QCD and a remaining $SU(3)$ with a large gauge boson mass m_C . To illustrate the situation, in Tab 1 we show the charge assignments of the different quark generations and the predicted sign of a forward-backward asymmetry [5]. We need $g_1 \neq g_2$ with a flipped axigluon charge assignment where the left-handed light-generation is aligned with the right-

$SU(3)_1$	$SU(3)_2$	ΔA_{FB}	
q_R	$(t, b)_L q_L t_R, b_R q_R$	$= 0$	coloron
	$(t, b)_L q_L t_R, b_R$	$= 0$	
	$(t, b)_L q_L q_R$	$= 0$	
t_R, b_R	$(t, b)_L t_R, b_R q_R$	$= 0$	candidate
q_L	$(t, b)_L q_R$	> 0	
$q_L t_R, b_R$	$(t, b)_L t_R, b_R$	$= 0$	
$q_L q_R$	$(t, b)_L q_L$	< 0	axigluon
$t_R, b_R q_R$	$(t, b)_L$	$= 0$	

Table 1: $SU(3)_1 \times SU(3)_2$ charge assignments in different models and their forward-backward asymmetry prediction for top pairs at the Tevatron.

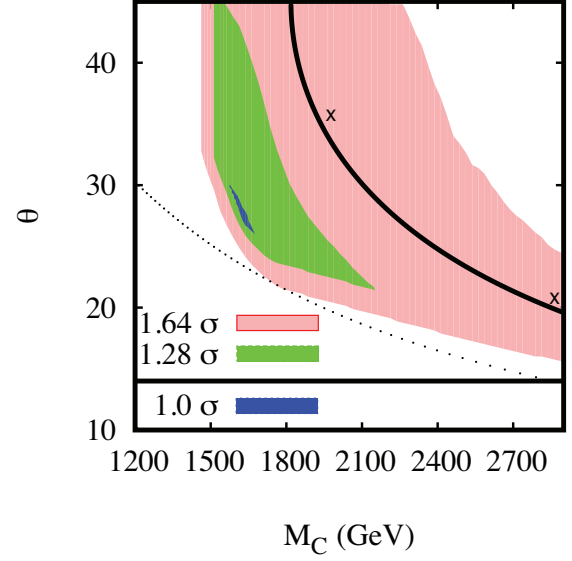


Fig. 2: Switched axigluon parameter space. Different levels of agreement with data correspond to the different shading. The solid black line shows the 95% CL limit from B_d mixing. The crosses correspond to parameter points for which the predicted Tevatron anomaly does not exceed 0.05.

handed 3rd generation. Their couplings in terms of the mixing angle have the structure $g_L^t \sim g_R^q \sim 1 - \cos^2 \theta$.

Studying such scenarios requires us to take into account additional constraints. B_d mixing in certain flavor models requires in terms of the mass and mixing angle $m_C \sin 2\theta > 1.8 \text{ TeV}$, while electroweak precision data implies $m_C > \cot \theta \times 700 \text{ GeV}$, as shown in Fig 2. Asymmetries resulting from switched axigluons respecting these constraints do not predict contributions exceeding $A_{\text{FB}} \sim 0.04$ and are hence not well suited to explain the Tevatron anomaly. Different flavor assumptions weaken these constraints but leave untouched the problem of generating the large observed asymmetry while staying in agreement with known constraints [6, 7].

Instead, at the LHC we have to search for models which might explain this asymmetry in channels which have nothing to do with the asymmetry. This includes colored particles which violate flavor in t channel exchange. Alternatively, we might see like-sign top pair production at the LHC. Luminosities of the order of 5 fb^{-1} at 7 TeV are already promising for such searches and might well tell us something about new physics at the TeV scale long before we get to test if it has anything to do with the Tevatron anomaly — or the hierarchy problem, for that matter.

3 Anomaly: dark matter

Of all experimental anomalies affecting the Standard Model the observed dark matter density is certainly the best established [8]. The WIMP miracle implies that a weakly interacting dark matter particle needs a mass around the TeV scale to reproduce the observed relic density of cold dark matter. This might or might not be a coincidence, but for new physics models it is a strong motivation to introduce a stable new particle. Its stability can be ensured by a Z_2 symmetry which as a side effect can protect the model from electroweak precision data.

In the popular minimal supersymmetric Standard Model, the dark matter candidate is a Majorana fermion with only weak charge. The scalar neutrino could serve the same purpose, but comparing its annihilation rate to the observed relic density with direct detection rules is out. In its short life time the PAMELA anomaly motivated studies of a Dirac gaugino which would naturally prefer to annihilate to leptons and not to quarks. Finally, in models with universal extra dimensions the dark matter candidate is the Kaluza-Klein partner of the neutral weak gauge bosons. The lesson to learn from these exercises in model building is that even if we assume that our dark matter agent is a WIMP, we should not only look for a Majorana fermion.

An interesting observation is that at the amplitude level we can link the scattering of a WIMP off a nucleon

	operator	coefficient
D1	$\bar{\chi}\chi\bar{q}q$	m_q/Λ^3
D2	$\bar{\chi}\gamma^5\chi\bar{q}q$	im_q/Λ^3
D3	$\bar{\chi}\chi\bar{q}\gamma^5q$	im_q/Λ^3
D4	$\bar{\chi}\gamma^5\chi\bar{q}\gamma^5q$	m_q/Λ^3
D5	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	$1/\Lambda^2$
D6	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	$1/\Lambda^2$
D7	$\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5q$	$1/\Lambda^2$
D8	$\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5q$	$1/\Lambda^2$
D9	$\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	$1/\Lambda^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\alpha\beta}q$	i/Λ^2
D11	$\bar{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4\Lambda^3$
D12	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4\Lambda^3$
D13	$\bar{\chi}\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$i\alpha_s/4\Lambda^3$
D14	$\bar{\chi}\gamma^5\chi G_{\mu\nu}\tilde{G}^{\mu\nu}$	$\alpha_s/4\Lambda^3$

Table 2: Operators coupling a Dirac fermion dark matter candidate to Standard Model particles and their scaling in terms of an effective theory.

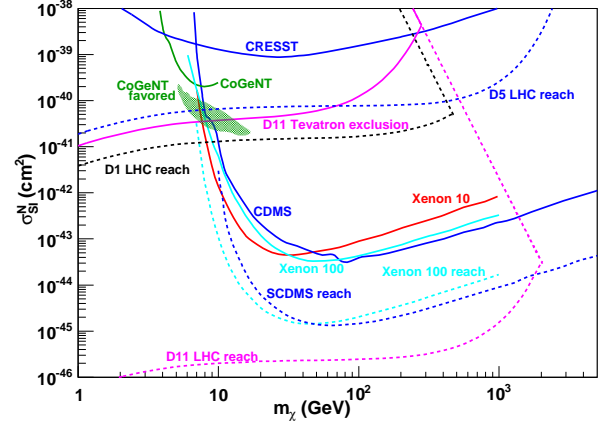


Fig. 3: Limits on Dirac fermion dark matter from spin-independent direct detection searches and (projected) from LHC, based on the operators in Tab 2.

in direct detection with WIMP pair production at the LHC

$$q\chi \rightarrow q\chi \quad \Leftrightarrow \quad q\bar{q} \rightarrow \chi\chi^*, \quad (4)$$

where the star generically implies the anti-WIMP. Such a process can for example be mediated by an s -channel Z or Higgs boson or a t -channel partner of the quark, if such a particle should exist. For supersymmetry similar links have been successfully established between direct detection experiments and pseudoscalar Higgs production at colliders, while any correlation is absent between dark matter observables and neutralino-chargino pair production decaying to tri-leptons [9].

Avoiding specific models, to a given dimension we can list all operators which can mediate these processes for a Dirac fermion dark matter candidate in Tab 2 [10]. Similar lists we can produce to a Majorana fermion or real or complex scalars. Note that this list of operators includes those for example mediated by t -channel squarks in the case of supersymmetry, but in the limit of decoupled squarks.

This list of operators we can analyze for the direct detection and for the collider direction of the process shown in Eq.(4). In Fig 3 we see how for example spin-independent direct detection and LHC reaches compare [10]. The only caveat of such a comparison is that it might drastically underestimate the LHC reach, since at hadron colliders we can produce any light enough strongly interacting particle directly and should not integrate it out in an effective theory. Squark pair production decaying to neutralinos in supersymmetry is a good example for this situation, with $\sigma(\tilde{q}\tilde{q} \rightarrow \chi\chi + X) \gg \sigma(\chi\chi)$.

4 Models: Dirac gauginos

A major problem with the minimal supersymmetric Standard Model are the many constraints from the flavor sector, including electric dipole moments. While a complete absence of any signal for new physics can be considered a sign for particular symmetry structures at and beyond the TeV scale they are also worrisome. The question arises, if it is possible to alleviate the pressure the non-observation of any higher-dimensional flavor operators puts on the MSSM.

One way to do this is to promote the R parity we need to prevent proton decay and to stabilize a dark matter candidate to a continuous global symmetry. If we also avoid spontaneous supersymmetry breaking such a symmetry forbids a fair fraction of soft breaking terms, including Majorana masses, tri-scalar interactions, or the μ term. The absence of these terms gets rid of many dimension-5 flavor violating operators, but it leaves open how to give mass for example to the gluino [11]. With two degrees of freedom mirroring the two gluon polarizations the gluino stays massless unless we identify two additional degrees of freedom to generate a Dirac mass. The solution is to introduce a complex scalar sgluon [12] with a Standard Model R charge. This sgluon we can also interpret as a result of an extended $N = 2$ supersymmetry which allows us to consistently extrapolate between Majorana and Dirac gluino masses in a phenomenological analysis [13]. The same feature of course appears for the weak gauginos, but its experimental signatures are much less generic.

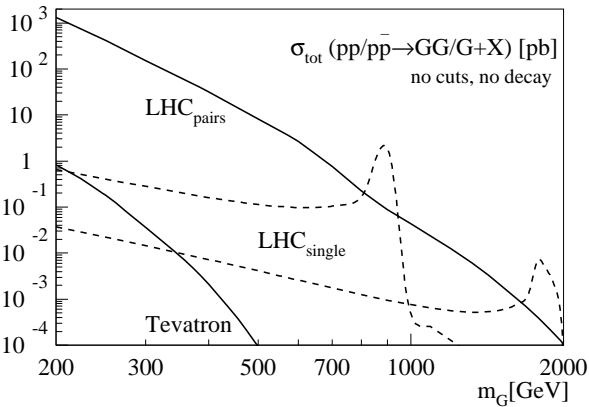


Fig. 4: Cross sections for sgluons at the Tevatron and a 14 TeV LHC. For the LHC we show pair (solid) and single production (dashed). The two curves for single sgluon production assume a gluino mass of 1 TeV and squark masses of 500 GeV (upper) and 1 TeV (lower).

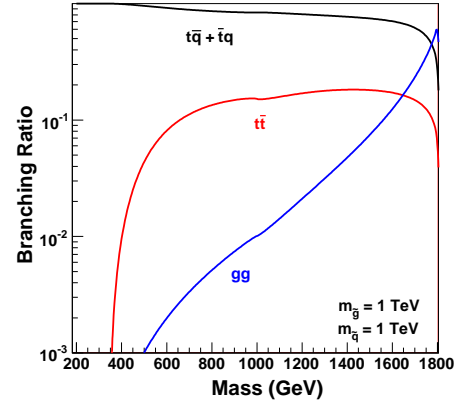


Fig. 5: Sgluon branching ratios for different left-handed squark and gluino masses. Right-handed squarks are set to 90% of the left-handed squark masses. We assume maximal up-squark mixing.

From regular minimal supersymmetry we know that the SUSY-QCD sector is especially predictive. The same is the case for the gluino-sgluon sector: the sgluon's adjoint color charge fixes the gluon-sgluon-sgluon coupling, supersymmetry predicts a strong sgluon-gluino-gluino coupling, and D terms determine the strong squark-squark-sgluon-sgluon coupling. This fully determines the pair production cross section at hadron colliders.

Couplings involving a single sgluon, relevant for single production or sgluon decays, are generated at the one-loop level. As we can see in Fig 4 the pair production rate exceeds single production unless on-shell effects inside the loop enhance the latter. An interesting structure appears in the quark-quark-sgluon coupling which is proportional to the quark mass and due to the weakened flavor constraints does not have to be flavor diagonal. In Fig 5 we see how only fairly heavy sgluons will not decay to $q\bar{t} + t\bar{q}$ but to a pair of gluon jets. At the LHC we would observe two like-sign tops, each together with a hard jet reconstructing the sgluon.

An interesting alternative search is based on ignoring the motivation of the R -symmetric MSSM and instead look for generic multi-jet final states without leptons or missing energy or any other distinctive feature but a set of mass constraints. Any kind of color octet like axigluons (as discussed in Sec 2), colorons, or heavy gluon partner predicts such signatures. In the case of colorons it has been nicely shown how given enough hard jets and mass constraints we can not only identify a new physics signature but also determine the masses of the particle involved [14].

5 Models: four generations

Searches for four generations are an obvious task for the LHC, given that the number of chiral fermion generations is not linked to any property of the Standard Model as a field theory. There exists a multitude of motivations for four generations, weakly as well as strongly interacting, with and without supersymmetry, etc.

Arguments used against four generations include

- mass degenerate heavy up and down quarks are forbidden by electroweak precision data — the top and bottom mass in the Standard Model are not degenerate, either, and a 10% mass splitting cures this problem [15].
- the theory might become strongly interacting at large energies — this might either lead to electroweak symmetry breaking [16] or be absent due to the fixed point structure of the Yukawas and the Higgs self coupling [17].
- a generic unhappiness with heavy fourth generation neutrinos — which can be avoided altogether for some more exotic unified group representations [18].
- or simply the feeling that ‘there should not be a fourth generation’ [19].

Obviously, there exist at least as good arguments against supersymmetry, extra dimensions, or strongly interacting Higgs models. An easy way to cure the problem with electroweak precision data is shown in Tab 3: with the correct ordering and a small splitting between the heavy u_4 and d_4 quarks we move along the main axis of the S vs T ellipse. As a side effect any Higgs mass is allowed in these models.

A likely effect of electroweak precision data, but not unsurmountable [20] is that the heavy u_4 should decay

m_{u_4}	m_{d_4}	m_H	ΔS_{tot}	ΔT_{tot}
310	260	115	0.15	0.19
320	260	200	0.19	0.20
330	260	300	0.21	0.22
400	350	115	0.15	0.19
400	340	200	0.19	0.20
400	325	300	0.21	0.25

Table 3: ΔS and ΔT from a fourth generation. The lepton masses are $m_{\nu_4} = 100$ GeV and $m_{\ell_4} = 155$ GeV, giving $\Delta S_{\nu\ell} = 0.00$ and $\Delta T_{\nu\ell} = 0.05$. All points are within the 68% CL contour defined by the LEP EWWG.

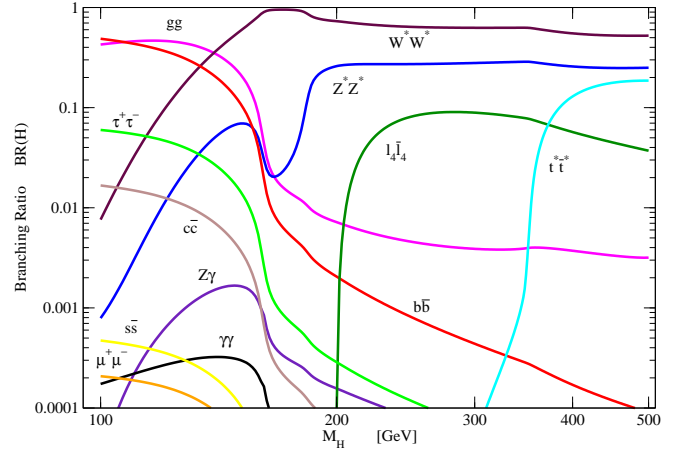


Fig. 6: Higgs branching ratios based on the mass spectrum shown in the second line in Tab 3. The numbers are obtained with a modified version of HDECAY [21].

to the d_4 and not vice versa. This could give rise to decay cascades of the kind

$$u_4 \rightarrow (W d_4) \rightarrow (W W t) \rightarrow (W W W b), \quad (5)$$

observable for example as many like-sign leptons.

Chiral fermions have the particular property that they do not decouple from a theory. For example, in the dimension-5 gluon-gluon-Higgs coupling the Yukawa coupling in the numerator cancels the decoupling heavy mass in the denominator. For any quark the coupling is only suppressed by the Higgs VEV and approaches a constant value for large quark masses and Yukawas. A fourth quark generation roughly triples the effective Higgs coupling to gluons or increases the leading LHC cross section for Higgs production by a factor 9. For small Higgs masses such an enhancement is ruled out by the Tevatron, but this constraint vanishes if the Higgs becomes heavier according to Tab 3. For small Higgs masses the tree-level decays to tau leptons and b quarks are surpassed by the similarly enhanced loop induced decay to two gluons, which will essentially be invisible at the LHC. For large Higgs masses the decays to W and Z bosons which in the heavy Higgs limit scale like 2:1 are unaffected.

When we add supersymmetry to models with a fourth generation we see two interesting effects: first, electroweak baryogenesis can be revived with a fairly small mass splitting between fourth generation quarks and squarks. Second, we can generate the entire light CP-even Higgs mass via loop effects and avoid the little hierarchy problem altogether. We might even see a supersymmetric light CP-even Higgs decaying to W pairs [22].

6 Analysis: boosted tops

Looking for new physics using boosted heavy Standard Model particles decaying to quarks or gluons (W, H, t) has long been recognized as a motivation to study not only the outcome of a jet algorithm, but also the clustering history [23]. Recently, this strategy has revived a major search channels for a light Higgs at the LHC, namely WH/ZH production with $H \rightarrow b\bar{b}$ [24]. Already from the first attempts to use fat jets from massive particles [23] we know that hadronic top decays are promising candidates to solve combinatorial issues as well as improve the mass resolution of the particles decaying to tops.

One of the standard top taggers inspired by the $H \rightarrow b\bar{b}$ analysis [24] is the Johns Hopkins tagger, optimized for heavy resonances decaying to very strongly boosted top pairs [25]. The problem of any such specialized taggers is that they are unlikely to be tested in the Standard Model $t\bar{t}$ sample and that their range of applications is limited. In Fig 7 we show the correlation of kinematic parameters we expect for more or less boosted top decay products [26]. A maximum usable jet size around $R = 1.5$ translates into a transverse momentum $p_{T,t} > 200$ GeV. The challenge is to construct a top tagger which works down to this kind of transverse momenta.

The publicly available HEPTOPTAGGER [26] has been shown to resolve the combinatorial and background issues in $t\bar{t}H$ searches, but the required integrated luminosities around 100 fb^{-1} would benefit from further experimental studies. The tagging efficiencies we show in Fig 8. Typical mis-tagging rates on QCD or W +jet events range around a few per-cent. A detailed ATLAS

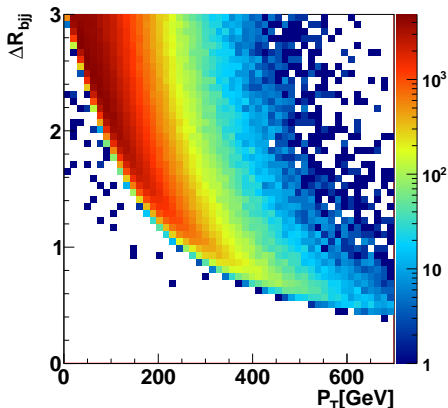


Fig. 7: Top pair events at the LHC as a function of the transverse momentum and an approximate R size needed to cover all decay products.

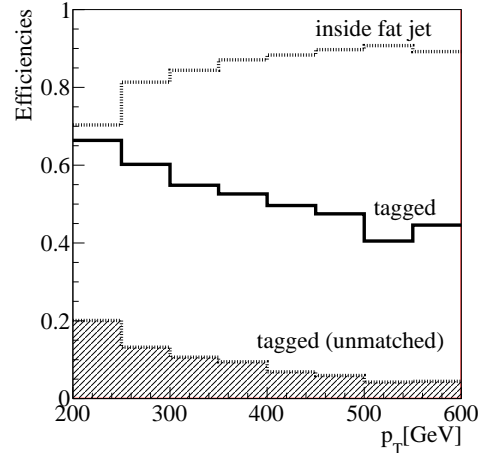


Fig. 8: HEPTOPTAGGER efficiencies evaluated on $t\bar{t}$ events normalized to all tops covered by a jet size $R = 1.5$. The unmatched fraction indicated events where our naive geometric mapping of tagged tops to Monte Carlo truth is not unique.

study is on the way.

As mentioned in the Introduction, we might well observe for example a top partner helping to stabilize the Higgs mass before we see the Higgs boson itself. Searching for top partners decaying flavor-diagonally to a top quark and a weakly interacting dark matter agent (as discussed in Sec 3) is one of the best motivated dedicated searches at the LHC.

Without the help of a top tagger searching for top partners decaying to hadronic or semi-leptonic top pairs is not promising due to overwhelming systematic uncertainties and a limited signal-to-branching ratio $S/B \sim 1/10$ [26]. In contrast, a successful hadronic analysis based on tagged tops is essentially the same as a slepton or sbottom pair search where we reconstruct the decay lepton's or bottom's 4-momentum and apply an $M_{T,2}$ cut. It allows us to extract the stop signal for stop masses from $350 - 650$ GeV at a 14 TeV LHC with luminosities around 10 fb^{-1} . Moreover, the clearly visible endpoint of the $M_{T,2}$ distribution determines the stop mass given the mass of the dark matter candidate. Because we can fully rely on the reconstructed top 4-momentum we do not make use of angular correlations, making such an analysis easily generalizable.

An obvious question is if we can extract boosted semileptonic stop pairs based on one hadronic and one leptonic tag. It turns out feasible with luminosities comparable to the hadronic mode, but with a less impressive leptonic 4-momentum reconstruction [27].

7 Analysis: inclusive jet searches

Recently, the first LHC results on searches for new physics — specifically for supersymmetry — in jets plus missing energy, plus zero leptons [28]. The questions, following for example the first CMS paper, is how general we can keep these searches and to what degree we need to apply specific background rejection cuts to improve the results of counting experiments.

Ideally, we would only apply a minimal set of cuts to reduce the pure QCD and W/Z +jets backgrounds to a manageable level with respect to systematic uncertainties, namely $\cancel{p}_T > 100$ GeV and no hard lepton. Two key observables when looking at QCD final states are the number of jets n_{jets} and the effective mass m_{eff} in its most inclusive definition $m_{\text{eff}} = \cancel{p}_T + \sum_{\text{all jets}} p_{T,j}$. Both observables we compute taking into account all jets which fulfill $|\gamma_j| < 4.5$ and $p_{T,j} > 50$ GeV. The problem with the n_{jets} and m_{eff} distributions is that they are theoretically not well studied. Experimentally, we know that the inclusive n_{jets} distributions shows the so-called staircase scaling [29]

$$\frac{\sigma_{n+1}}{\sigma_n} = R_{(n+1)/n} = \text{const}, \quad (6)$$

which holds equivalently for inclusive and exclusive jet

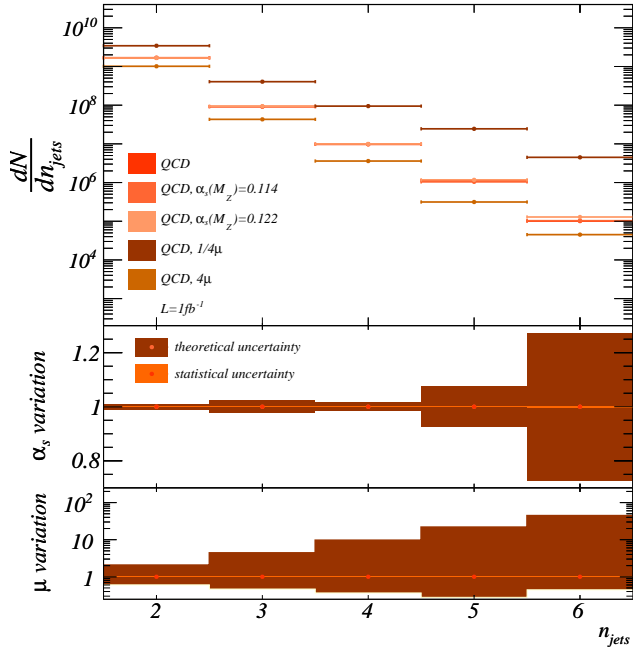


Fig. 9: Exclusive $d\sigma/dn_{\text{jets}}$ distribution for QCD jets. The second panel shows the parametric uncertainty due to $\alpha_s(M_Z)$. The third panel shows the consistent scale factor treatment which can be experimentally determined.

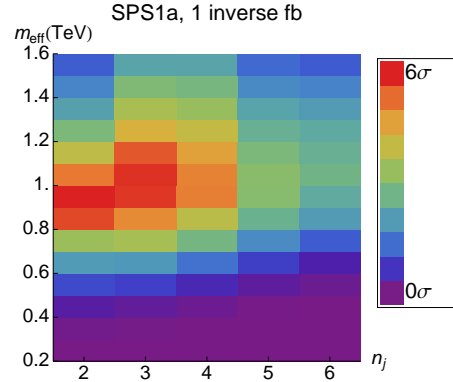


Fig. 10: $(n_{\text{jets}}, m_{\text{eff}})$ plane for the supersymmetric SPS1a signal showing the individual log-likelihoods in each bin.

rates [30]. From a statistics point of view, we clearly prefer the exclusive n_{jets} distribution where each event is only assigned to one bin.

In Fig 9 we show how this exclusive scaling can be simulated using CKKW merging as implemented in SHERPA [31]. What is crucial to use this scaling as background estimates in new physics searches is to understand the uncertainties. First, we estimate the theory uncertainty due to a consistent variation of $\alpha_s(M_Z)$ in the matrix elements, the parton shower, and the parton densities. This error bar is manageable and might be comparable to the experimental systematics or to statistical errors after the basic background rejection cuts mentioned above.

The bottom panel shows the naive error estimate from varying all factorization and renormalization scales around a central value $\mu/\mu_0 = 1/4 - 4$. This scale factor cannot be derived from first principles. However, we can estimate it from data and find that in SHERPA it should essentially be unity. Determining this scale factor and fixing the normalization of the two-jet rate from experiment allows us to within a well defined theory uncertainty predict the n_{jets} and m_{eff} distributions for QCD and W/Z +jets backgrounds. Of course, for the new physics channels we need to rely on simulations for both distributions [1, 12, 30].

From a theory point of view, these two distributions are particularly interesting because m_{eff} is correlated with the mass of the new strongly interacting particles and n_{jets} is largely determined by their color charge. In Fig 10 we show this two-dimensional correlation which we can understand in terms of the different squark and gluino production channels.

8 Exciting times ahead

The way I organized this review should be considered a discussion of recent papers I personally found interesting right before I presented them at Physics in Collisions 2010. It is not meant to be an overview of recent developments or a thorough review of classical new physics at the LHC. For the latter, please look at our comprehensive review article Ref [1]. Along the same lines, I did not make any attempt to cover the literature on the seven topics I discussed in the individual sections. An appropriate coverage of the relevant publications should be found in the individual papers or newer publications which have appeared since I gave this talk in the Fall of 2010.

What I wanted to illustrate are four different ways to approach new physics searches at the LHC, in particular in the early stage of LHC data analysis. Lacking better guidance we can follow a very pragmatic approach asking what we can actually see given a certain experimental performance. Second, we can follow more or less well established experimental anomalies like the top forward-backward asymmetry, weakly interacting dark matter, or any other anomaly to our liking. Third, we can let ourselves be inspired by new developments or frequent recurrences in TeV-scale model building. Finally, we can get most excited about progress in LHC analysis techniques, like for example fat jets, and new opportunities they give us. All these approaches are equally well motivated and honorable, given that we might well need to look for the solution of the TeV-scale puzzle before getting to look at the Higgs sector or the structure of electroweak symmetry breaking in any detail.

What is neither well motivated nor honorable is to let our individual perspective bias our view of new physics searches: we simply do not know what to look for at the LHC. Whatever we might find will at least prove most of us, possibly all of us wrong. This makes it crucial to set up and interpret searches in the most general framework we can. While there does not exist any such thing as a feasible general search for physics beyond the Standard Model at the LHC, for example looking for the supersymmetric parameter point SPS1a' at the LHC makes no sense. Structures have to be inferred from observation not included in the analysis. A particularly bad example is the recent CMS analysis [28] which presents the results of the first supersymmetry search in terms of m_0 and $m_{1/2}$. Because there does not

exist a mapping from the m_0 vs $m_{1/2}$ to the physical squark and gluino mass plane the presentation of the results deliberately excludes scenarios in which the gluino is significantly heavier than the squark. What the authors seem to not be aware of is that topologically an ellipse (constant squark mass) and a straight line (constant gluino mass) do not have to meet.

Coming back, the wide open field of new physics is, in my opinion, the most exciting aspect of LHC searches. Because ATLAS and CMS are multi-purpose experiments we are not waiting for one specific observable, like for example the anomalous magnetic moment of the muon, to either agree or disagree with the Standard Model predictions. Developments in model building and phenomenology have shown that new physics at the TeV scale will very generically be discovered at the LHC, so we can freely choose between the four sources of inspiration listed above, or anything else.

I would like to end this proceedings article with a quote by Uli Baur, who passed away not only much too early in his life but also at the most annoying time in his personal physics agenda. Even though Uli himself will not see the physics discoveries he was looking forward to for decades I remember his motivation for new physics searches: We will always discover new physics when we look at much higher energy scales.

I would like to thank many colleagues for their insightful comments, including Uli Haisch and Susanne Westhoff on flavor constraints on axigluons and Graham Kribs and Tim Tait on almost all topics discussed in this talk.

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